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(54) **USE OF MULTIPLE STORAGE CAVERNS FOR PRODUCT IMPURITY CONTROL**

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(71) Applicant: **Air Liquide Large Industries U.S. LP**,
Houston, TX (US)

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(72) Inventor: **Ronald Strybos**, Kountze, TX (US)

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(73) Assignee: **Air Liquide Large Industries U.S. LP**,
Houston, TX (US)

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(52) **U.S. Cl.**

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(74) *Attorney, Agent, or Firm* — Elwood L. Haynes

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See application file for complete search history.

(57)

ABSTRACT

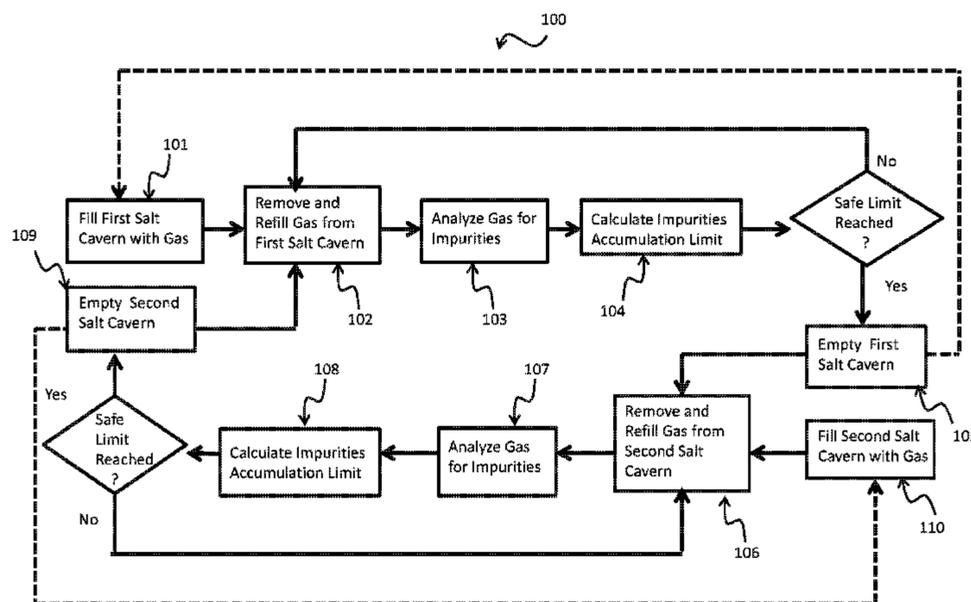
An inventory management method is also provided. This method includes removing and replacing the gas product from a first salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the first salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the first salt cavern, while concurrently, removing and replacing the gas product from a second salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the second salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the second salt cavern, while concurrently repeating steps a)-g).

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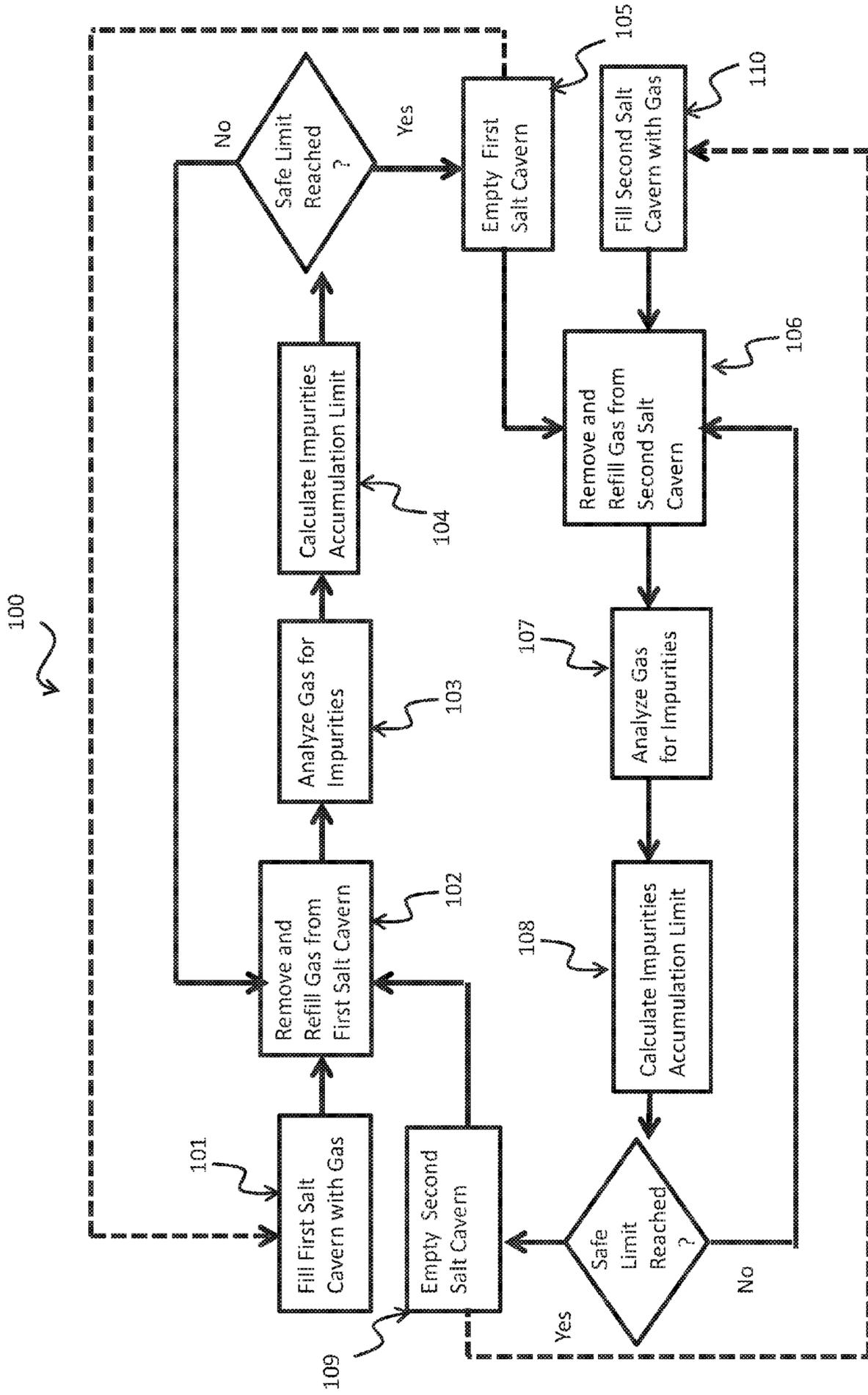


Figure 1

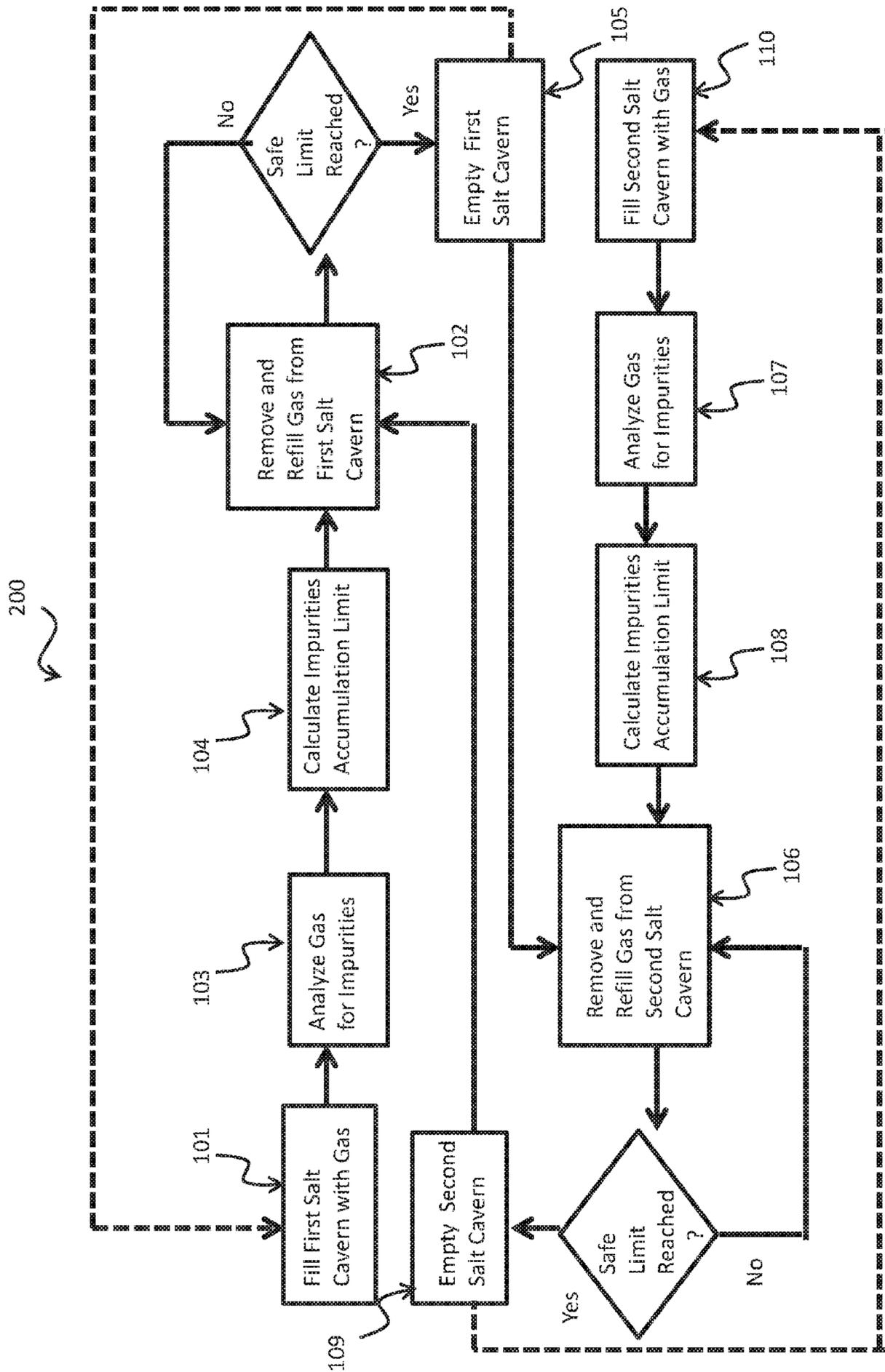


Figure 2

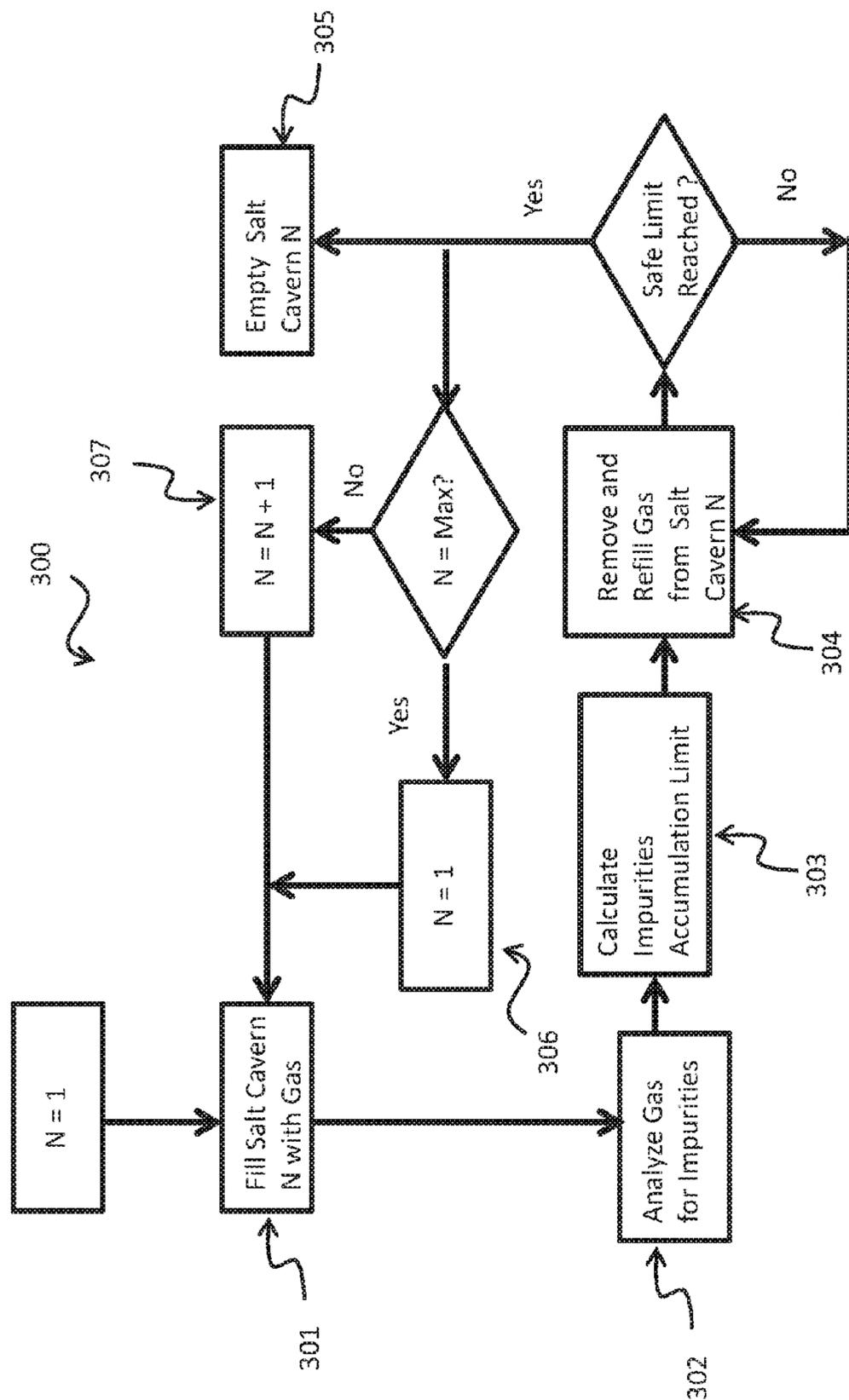


Figure 3

USE OF MULTIPLE STORAGE CAVERNS FOR PRODUCT IMPURITY CONTROL

BACKGROUND

The storage of gases and liquids in solution mined salt caverns, whether leached in domal or stratified salt formations can result in contamination of the stored product by, for example, egress of impurities from the salt formation and overburden outside the salt formation. The stored products typically include hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix (LPG), butane, or pentane.

Typical impurities include, but are not limited to, hydrogen sulfide (H₂S), methane (CH₄), carbon dioxide (CO₂), nitrogen (N₂), ethane (C₂H₆), benzene (C₆H₆) and other naturally occurring hydrocarbons (C_xH_x). These impurities were found to enter the salt cavern from two sources, either gas bubbles trapped in the salt formation or methane gas entering the cavern through fractures and weak seams.

In a single cavern storage configuration, it was found that impurities accumulate in the stored product and increase over time, causing the product to not meet commercial specification.

SUMMARY

One embodiment of an inventory management method is provided. This method includes introducing a gas product into a first salt cavern and a second salt cavern, removing and replacing the gas product from the first salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the first salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the first salt cavern, while concurrently, removing and replacing the gas product from the second salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the second salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the second salt cavern, while concurrently repeating steps b)-h).

Another embodiment of an inventory management method is also provided. This method includes removing and replacing the gas product from a first salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the first salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the first salt cavern, while concurrently, removing and replacing the gas product from a second salt cavern as supply and demand dictate, analyzing the impurities in the gas product that is removed, predicting the duration until a maximum acceptable impurity limit is present, removing all the working gas from the second salt cavern when the maximum acceptable impurity limit is reached, then replacing the working gas in the second salt cavern, while concurrently repeating steps a)-g).

Another embodiment of an inventory management method is provided. This method includes introducing a gas product into a first salt cavern and a second salt cavern, analyzing the impurities in the gas product, predicting the duration until a maximum acceptable impurity limit is

present, removing and replacing the gas product from the first salt cavern as supply and demand dictate, removing all the working gas from the first salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas in the first salt cavern, while concurrently, removing and replacing the gas product from the second salt cavern as supply and demand dictate, removing all the working gas from the second salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas from the second salt cavern, while concurrently repeating steps b)-f).

Another embodiment of an inventory management method is provided. This method includes analyzing the impurities in the gas product, predicting the duration until a maximum acceptable impurity limit is present, removing and replacing the gas product from the first salt cavern as supply and demand dictate, removing all the working gas from the first salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas in the first salt cavern, while concurrently, removing and replacing the gas product from the second salt cavern as supply and demand dictate, removing all the working gas from the second salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas from the second salt cavern, while concurrently repeating steps b)-e).

Another embodiment of an inventory management method is provided. This method includes introducing a gas product into Q salt caverns, where Q is a number greater than 1, setting cavern counter N to 0, if N=Q, setting salt cavern counter to N=0, if N<Q, setting salt cavern counter to N=N+1, removing and replacing the gas product from salt cavern N as supply and demand dictate, analyzing the impurities in the gas product that is removed from salt cavern N, predicting the duration until a maximum acceptable impurity limit is present in the product gas removed from cavern N, removing all the working gas from salt cavern N when the maximum acceptable impurity limit is reached, then replacing the working gas in salt cavern N, while concurrently, repeating steps b)-f).

Another embodiment of an inventory management method is provided.

This method includes if N=Q, setting salt cavern counter to N=0, if N<Q, setting salt cavern counter to N=N+1, removing and replacing the gas product from salt cavern N as supply and demand dictate, analyzing the impurities in the gas product that is removed from salt cavern N, predicting the duration until a maximum acceptable impurity limit is present in the product gas removed from cavern N, removing all the working gas from salt cavern N when the maximum acceptable impurity limit is reached, then replacing the working gas in salt cavern N, while concurrently, repeating steps a)-e).

The gas product may be selected from the group consisting of hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix, butane, and pentane. The impurities may be selected from the group consisting of hydrogen sulfide, methane, carbon dioxide, nitrogen, ethane, and benzene.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 illustrates one embodiment of the present invention.

FIG. 2 illustrates another embodiment of the present invention.

FIG. 3 illustrates another embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Illustrative embodiments of the invention are described below. While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the invention to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developer's specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

In a single cavern storage configuration, it was found that impurities accumulate in the stored product and increase over time, causing the product to not meet commercial specification. This invention claims that by utilizing an inventory management system and multiple caverns the impurity concentrations are minimized. Multiple caverns can be two or more caverns that the same products are stored in. The caverns are connected on the surface by pipeline and pump or compressor stations.

Definitions of terms used herein:

Primary cavern—the main cavern used to store products and provide products to customers.

Reserve cavern—the cavern used as the back up to store products and provide products to customers.

Base gas—the volume of gas that is the permanent inventory of the cavern, and is used to maintain adequate minimum pressure within the cavern.

Working gas—the volume of gas in the cavern in addition to the base gas, and is available to supply customer demands.

Turning now to FIG. 1, one embodiment of an inventory management method **100** is provided. As shown in FIG. 1, the method **100** includes introducing a gas product into a first salt cavern **101** and a second salt cavern **110**. The gas product can be hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix, butane, or pentane. The gas product is introduced to the first salt cavern and stored under pressure.

Under normal operation, the gas product is removed from the first salt cavern during times of high demand and/or low availability, and the gas product is replaced in the first salt cavern during times of low demand and/or high availability **102**. Over time, various impurities will accumulate in the gas stored in the first cavern. These impurities may include hydrogen sulfide, methane, carbon dioxide, nitrogen, ethane, and/or benzene. As the gas is removed from the first cavern, the impurities are analyzed **103**. A prediction is made based on this analysis, as to the length of time that the first cavern may be operated before a maximum acceptable impurity limit is present in the first cavern **104**. This maximum acceptable impurity limit is established based on customer

requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

If the predicted maximum acceptable impurity limit (safe limit) has not been reached, gas continues to be removed from the first cavern. Once the predicted maximum acceptable impurity limit is reached, all of the working gas is allowed to be removed from the first salt cavern **105**. Concurrently, under normal operation, the gas product is now removed from the second salt cavern during times of high demand and/or low availability, and the gas product is replaced in the second salt cavern during times of low demand and/or high availability **106**. Once the working gas has been removed, and only the base gas remains, the first cavern is refilled with fresh gas product from the associated pipeline **101**.

Now, as the gas is removed from the second cavern, the impurities are analyzed **107**. A prediction is made based on this analysis, as to the length of time that the second cavern may be operated before a maximum acceptable impurity limit is present in the second cavern **108**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

If the predicted maximum acceptable impurity limit (safe limit) has not been reached, gas continues to be removed from the second cavern. Once the predicted maximum acceptable impurity limit is reached, all of the working gas is now allowed to be removed from the second salt cavern **109**. Concurrently, under normal operation, the gas product is now removed again from the first salt cavern during times of high demand and/or low availability, and the gas product is replaced in the first salt cavern during times of low demand and/or high availability **102**. Once the working gas has been removed, and only the base gas remains, the second cavern is refilled with fresh gas product from the associated pipeline **110**. As the gas is removed from the first cavern, the impurities are analyzed **103**. And the alternating cycle continues, with each salt cavern being emptied and refilled once the maximum acceptable impurity limit is reached, while the other salt cavern takes over with satisfying customer demands.

Turning now to FIG. 2, another embodiment of an inventory management method **200** is provided. In the interest of clarity, as the various method steps in FIG. 2 are identical to those of FIG. 1, the same element numbers are used.

As shown in FIG. 2, the method **200** includes introducing a gas product into a first salt cavern **101** and a second salt cavern **110**. The gas product can be hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix, butane, or pentane. The gas product is introduced to the first salt cavern and stored under pressure.

Over time, various impurities will accumulate in the gas stored in the first cavern. These impurities may include hydrogen sulfide, methane, carbon dioxide, nitrogen, ethane, and/or benzene. As the gas is removed from the first cavern, the impurities are analyzed **103**. A prediction is made based on this analysis, as to the length of time that the first cavern may be operated before a maximum acceptable impurity limit is present in the first cavern **104**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

The difference between inventory management method **100** and inventory management method **200**, is that in

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method **100** the analysis and calculation/prediction of impurities is done as a feedback loop. With each new gas analysis, additional prediction accuracy may be possible. The frequency of the analysis, and hence the frequency with which the impurity prediction is made is a design choice made by the skilled artisan. In method **200**, the analysis and calculation/prediction of impurities is done in a feed forward fashion. The analysis is made of the gas, and based, for example, on historical data, the estimated time that the cavern must be discontinued and emptied is predicted.

Under normal operation, the gas product is removed from the first salt cavern during times of high demand and/or low availability, and the gas product is replaced in the first salt cavern during times of low demand and/or high availability **102**.

Once the predicted maximum acceptable impurity limit is reached, all of the working gas is allowed to be removed from the first salt cavern **105**. Concurrently, the gas is now being removed from the second cavern. As the gas is removed from the second cavern, the impurities are analyzed **107**. A prediction is made based on this analysis, as to the length of time that the second cavern may be operated before a maximum acceptable impurity limit is present in the second cavern **108**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

Now, under normal operation, the gas product is removed from the second salt cavern during times of high demand and/or low availability, and the gas product is replaced in the second salt cavern during times of low demand and/or high availability **106**. Once the working gas has been removed, and only the base gas remains, the first cavern is refilled with fresh gas product from the associated pipeline **101**.

Once the predicted maximum acceptable impurity limit is reached, all of the working gas is now allowed to be removed from the second salt cavern **109**. Concurrently, under normal operation, the gas product is now removed again from the first salt cavern, analyzed, impurity threshold predicted, and during times of high demand and/or low availability, and the gas product is replaced in the first salt cavern during times of low demand and/or high availability **102**. Once the working gas has been removed, and only the base gas remains, the second cavern is refilled with fresh gas product from the associated pipeline **110**. And the alternating cycle continues, with each salt cavern being emptied and refilled once the maximum acceptable impurity limit is reached, while the other salt cavern takes over with satisfying customer demands.

Turning now to FIG. **3**, another embodiment of an inventory management method **300** is provided. Whereas the method descriptions provided for inventory management methods **100** and **200** were based on the presence of two working salt caverns, inventory management method **300** is more general, and is based on the presence of X caverns, where X is a number greater than 1, which are intended to be used on concert.

The description that follows uses the feed forward model seen above in inventory management method **200**, but one skilled in the art would recognize that this method may also be applied with the feedback model seen above in inventory management method **100**.

As shown in FIG. **3**, the method **300** includes introducing a gas product into salt cavern N **301**. In order to illustrate this system, the initial value for N is established to be 1, and the number of caverns in coordinated operation is 3. For the

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sake of clarity, as following method is navigated, the current value N will be illustrated in parentheses.

The gas product can be hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix, butane, or pentane. The gas product is introduced to the first salt cavern and stored under pressure.

Over time, various impurities will accumulate in the gas stored in cavern N (1). These impurities may include hydrogen sulfide, methane, carbon dioxide, nitrogen, ethane, and/or benzene. As the gas is removed from the salt cavern N (1), the impurities are analyzed **302**. A prediction is made based on this analysis, as to the length of time that cavern N (1) may be operated before a maximum acceptable impurity limit is present in the cavern N (1) **303**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

Under normal operation, the gas product is removed from salt cavern N (1) during times of high demand and/or low availability, and the gas product is replaced in salt cavern N (1) during times of low demand and/or high availability **304**.

Once the predicted maximum acceptable impurity limit is reached, all of the working gas is allowed to be removed from the salt cavern N (1) **305**. Now, cavern counter N (1) is either increased by 1 (N=2) **(307)** or reset to 1 (not applicable for this cycle) **(306)** depending on which cavern was most recently used and is now being emptied.

Concurrently, the gas is now being removed from the next salt cavern N (2). As the gas is removed from the salt cavern N (2) the impurities are analyzed **302**. A prediction is made based on this analysis, as to the length of time that salt cavern N (2) may be operated before a maximum acceptable impurity limit is present in salt cavern N (2) **303**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

Now, under normal operation, the gas product is removed from salt cavern N (2) during times of high demand and/or low availability, and the gas product is replaced in the salt cavern N (2) during times of low demand and/or high availability **304**. Once the working gas has been removed from cavern N (1), and only the base gas remains, cavern N (1) is refilled with fresh gas product from the associated pipeline **101**.

Once the predicted maximum acceptable impurity limit is reached, all of the working gas is allowed to be removed from the salt cavern N (2) **305**. Now, cavern counter N (2) is either increased by 1 (N=3) **(307)** or reset to 1 (not applicable for this cycle) **(306)** depending on which cavern was most recently used and is now being emptied.

Concurrently, the gas is now being removed from the next salt cavern N (3). As the gas is removed from the salt cavern N (3) the impurities are analyzed **302**. A prediction is made based on this analysis, as to the length of time that salt cavern N (3) may be operated before a maximum acceptable impurity limit is present in salt cavern N (3) **303**. This maximum acceptable impurity limit is established based on customer requirements, but will typically be a value below the minimum threshold for these impurities required in the associated pipeline specification.

Now, under normal operation, the gas product is removed from salt cavern N (3) during times of high demand and/or low availability, and the gas product is replaced in the salt cavern N (3) during times of low demand and/or high availability **304**. Once the working gas has been removed

from cavern N (2), and only the base gas remains, cavern N (2) is refilled with fresh gas product from the associated pipeline **101**.

Once the predicted maximum acceptable impurity limit is reached, all of the working gas is allowed to be removed 5 from the salt cavern N (3) **305**. Now, cavern counter N (3) is either increased by 1 (not applicable for this cycle) (**307**) or reset to 1 (applicable for this cycle) (**306**) depending on which cavern was most recently used and is now being emptied. 10

Once the working gas has been removed, and only the base gas remains, the next salt cavern in the sequence is refilled with fresh gas product from the associated pipeline **301**. And the alternating cycle continues, with each salt cavern being emptied and refilled once the maximum 15 acceptable impurity limit is reached, while the other salt cavern takes over with satisfying customer demands.

The inventory management method essentially includes the following steps:

1. Filling a salt cavern with product.
2. Analyzing the product for impurities.
3. Calculating how long the impurities will accumulate to make the product out of specification.
4. Fill the reserve cavern(s).
5. Empty the primary cavern before the impurity level 25 causes the cavern to go out of specification for impurities.
6. Repeat this process for each cavern to keep inventory within the quality specification.

What is claimed is:

1. An inventory management method, comprising:

- a) introducing a gas product into a first salt cavern and a second salt cavern,
- b) analyzing the impurities in the gas product,
- c) predicting the duration until a maximum acceptable impurity limit is present,
- d) removing and replacing the gas product from the first salt cavern as supply and demand dictate,
- e) removing all the working gas from the first salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas in the first salt cavern, while concurrently,
- f) removing and replacing the gas product from the second salt cavern as supply and demand dictate,
- g) removing all the working gas from the second salt cavern when the predicted maximum acceptable impurity limit duration is reached, then replacing the working gas from the second salt cavern, while concurrently repeating steps b)-f).

2. The inventory management method of claim 1, wherein 20 the gas product is selected from the group consisting of hydrogen, nitrogen, carbon dioxide, air, methane, ethane, ethylene, propylene, propane, ethane/propane mix, butane, and pentane.

3. The inventory management method of claim 1, wherein 25 the gas product is hydrogen.

4. The inventory management method of claim 1, wherein the impurities are selected from the group consisting of hydrogen sulfide, methane, carbon dioxide, nitrogen, ethane, and benzene.

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